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ART. XIV.—*The Crinanite Laccolith of Circular Head, Tasmania.*

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Introduction.

Circular Head is a prominent feature of the coast of North-West Tasmania well known both on account of its striking shape (Edwards, 1941) and its history. It owes its highly descriptive name to Bass and Flinders, who sighted it in December, 1798. Flinders (1814) describes is as "a cliffy lump, much resembling in form a Christmas cake, joined to the main by a sandy isthmus;" and in the Hobart Town Almanac for 1831 it is referred to as "that curious rock (which) stands like a huge round tower or fortress, built by human hands, which stretching out to sea, as if from the middle of a bay, is joined to the land by a narrow isthmus." It was here that the Van Dieman's Land Company established the first settlement in the North-West, in 1826.

As described elsewhere (Edwards, 1941) the Head is a tied island, joined to the main part of Stanley Peninsula by a Y-tombolo, which in 1826 still enclosed a marshy lagoon. The lagoon has been drained and converted into pasture land. The Head itself is composed of an igneous rock of a type unusual to Tasmania, and specimens submitted to Rosenbusch were described by him as trachydolerite (Twelvetrees, 1902).

Circular Head appears to be the remains of a small, steep-sided laccolith. As its name indicates, it is more or less circular in plan, with diameters between 800 and 900 yards. It consists of gigantic columns of igneous rock, 4 to 6 feet in diameter, and rising vertically to a height of 487 feet above sea-level. These columns are exposed in sheer cliffs, several hundred feet high, notably on the northern and south-eastern sides, with a fringe of steeply sloping scree around their bases. Inspection of the sea-bed from the top of the cliffs shows that a dark fringe of scree forms a ring of uniform width round Circular Head on all sides exposed to the sea, and no extension of the igneous rock exists in any of these directions. Similarly, on the landward side where the scree slopes are more gentle, because they are not so subject to erosion, there is clearly no continuation of the rock towards the main ridge of Stanley Peninsula.

On the north-western side, on the beach below the Stanley Cemetery, the scree overlies soft mudstones and grits, which are exposed in the wave-cut bench. These sediments, which are presumably of Permo-Carboniferous age, judging by their texture and disposition, dip at about 30°N., and underlie the whole of Godfrey's Beach, since they also occur in the wave-cut bench at the north-western end of the beach. Similar sediments outcrop on the southern side of Circular Head, between the old wharves and the new, where they are visible at low tide. Much weathered sediments overlain by scree deposits are exposed in a cutting opposite the Harbour Master's Office, at the entrance to the wharves; and behind the adjacent timber yard, where the talus deposits have been completely removed, and a quarry has been cut to provide extra platform space, the sediments are exposed as an uneven surface sloping down towards the north-east beneath the igneous rock. The contact appears to be more or less conformable, while the sandy sediments are very little metamorphosed beyond induration for a few inches below the contact.

At the contact, and for a few feet above, the igneous rock is chilled, and has an almost glassy texture. When followed upwards, the grain size increases, and the ferro-magnesian minerals, particularly the pyroxene, become more prominent. At a height of 100 to 150 feet above the chilled base, the pyroxene crystals are 2 to 3 mm. in diameter, and show a distinct concentration. They project on weathered surfaces, and give the rock a spotted appearance. Rising still higher up the columns the coarse grain size is maintained, but the proportion of pyroxene decreases, until near the top felspar appears to be the dominant constituent. This progressive change can be observed on all sides of the Head.

The upper surface of the headland is not flat, as appears from a distance, but slightly undulating. Two small valleys combine to form a hanging valley 80 feet deep, and 320 feet above sea-level, on the southern side.

It is presumed, therefore, that Circular Head represents the core of a small, dome-shaped laccolith. Subaerial erosion has removed the roof and wall rocks, and destroyed the original chilled top of the laccolith. Marine erosion of the soft Permo-Carboniferous sediments underlying the laccolith has undermined the floor of the laccolith around its margins, causing the igneous columns to collapse. In this way the walls of the remaining portion of the laccolith have steepened and increased in height as they have retreated. The undermining process must have begun subsequent to the extrusion of the Green Hills basalt flow which forms the main ridge of the Stanley Peninsula, and is still in progress. The various stages in the development of the headland are shown diagrammatically in fig. 1.

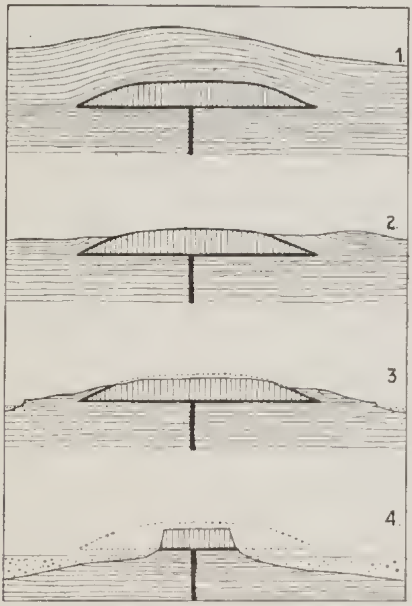

FIG. 1.—Diagrammatic representation of the development of Circular Head. 1. Intrusion of laccolith; 2. Unroofing; 3. Subaerial erosion; 4. Present stage, after undercutting by marine erosion.

Petrology.

The differentiation noted in the field is readily apparent when the proportions of the ferro-magnesian and other minerals in a series of specimens taken at successive levels from top to bottom of the laccolith are compared by micrometric analyses of thin sections (see Table I.).

TABLE I.—VARIATION IN MINERAL COMPOSITION WITH HEIGHT ABOVE CHILLED BASE.

Height Above Chilled Base.	Olivine.	Pyroxene.	Iron Ore.	Felspars, Groundmass, &c.
Feet.	Per cent	Per cent	Per cent	Per cent
440 (summit) ..	6·8	13·9	3·8	75·4
420	6·4	13·1	3·9	76·6
390	4·4	16·2	3·6	75·8
350	15·7	20·7	4·5	59·0
320	11·8	14·1	4·0	70·1
290	14·7	17·9	3·8	63·6
230	10·9	17·7	4·7	66·7
180	14·1	18·8	4·0	63·7
130	6·5	27·3	4·0	62·1
100	21·1	18·6	3·0	57·3
70	24·9	21·5	4·2	49·4
20	17·6	15·9	4·0	62·6
0 (base) ..	11·5	0·5	Nil	88·0

Comparison is aided by plotting the mineral percentage against elevation above the contact of the chilled base with the sediments, as has been done in fig. 2A. This shows that there is a marked concentration of the ferro-magnesian minerals in a narrow zone immediately above the "floor" provided by the chilled base of the laccolith. Above this zone the ferro-magnesians decrease steadily with increasing height above the "floor." The concentration of the ferro-magnesians in the lower part of the laccolith has displaced the felspathic and felspathoid constituents into

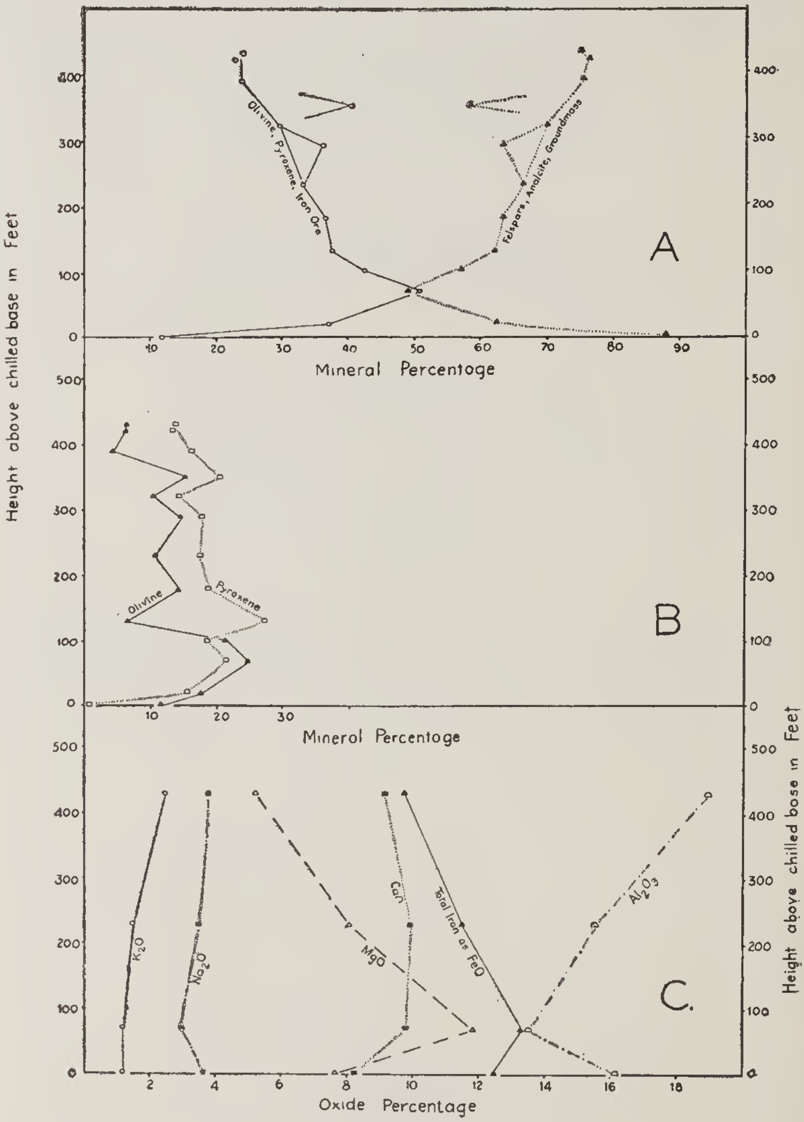

FIG. 2.—Variation profiles of the Circular Head Laccolith. A and B, Mineral Profiles; C, Oxide Profiles.

the upper levels. In fig. 2B, the ferro-magnesian graph of fig. 2A is analysed in terms of the two chief mafic components, olivine, and pyroxene. The olivine had commenced to crystallize prior to the emplacement of the magma, as is shown by its presence in the chilled base, whereas the pyroxene had not. As a result, the accumulation of olivine on the "floor" began before the pyroxene began to accumulate. Moreover, although the earlier-formed pyroxene formed as phenocrysts, and tended to sink, the later-formed pyroxene tended to form ophitic intergrowths with the plagioclase. This had the effect of buoying up such pyroxene. Some olivine, also, was prevented from sinking by becoming enclosed within the ophitic pyroxene. As a result, the gravitation of the pyroxene was less complete than that of the olivine, while the level of greatest accumulation of pyroxene extends above the level of greatest accumulation of olivine, and is not so sharply defined. Further, the sinking of the ferro-magnesian minerals did not proceed uniformly throughout the laccolith. As shown in fig. 2A, in some specimens the ferro-magnesian content greatly exceeds the general tenor of the surrounding rock, no doubt as a result of the "buoying up" factors noted above. In others, in which there is an unusual concentration of analcite (Table III.), there has been excessive removal of the ferro-magnesians probably because viscosity was reduced by the presence of abundant mineralizers. A number of other factors, such as the effects of convection currents close to the walls of the laccolith, may have contributed to these local variations.

The differentiation within the laccolith is equally well demonstrated by a series of chemical analyses of specimens from various levels, as is shown by Table II., and fig. 2C.

TABLE II.—CHEMICAL ANALYSES AT VARIOUS LEVELS IN THE LACCOLITH.

——	1.	2.	3.	4.	5.
SiO_2	44·75	43·35	45·70	46·15	48·05
Al_2O_3	16·15	13·50	15·52	18·95	21·33
Fe_2O_3	4·52	2·62	3·75	3 68	4·60
FeO	8·35	10·94	8·14	6·41	4·96
MgO	7·68	11·84	8·04	5·20	2·03
CaO	8·20	9·85	9·95	9·15	6·10
Na_2O	3·68	3·02	3·51	3·79	5·18
K_2O	1·18	1·18	1·51	2·43	4·28
H_2O	0·25	0·15	0·19	0·20	0·20
H_2O	1·74	0·71	0·70	1·49	1·72
CO_2	Nil	Nil	Nil	Nil	Nil
TiO_2	2·25	2·25	2·35	1·65	1·95
P_2O_5	0·71	0·83	1·08	0·50	0·25
MnO_2	0·11	0·10	0·10	0·10	0·12
	99·57	100·34	100·54	99·70	100·77

1. Chilled base at contact, behind timber yard, main wharf.
2. Olivine-rich layer, 70 feet above chilled base, same locality.
3. Two hundred and thirty feet above the chilled base, north-western side.
4. Summit, at 487 feet, or 440 feet above chilled base.
5. Nepheline-rich phase of the crinanite, not *in situ*.

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The magnesia content of the analysed specimens shows a sharp increase in the olivine-rich layer, and then decreases in the higher layers. Total iron behaves similarly, though the change from specimen to specimen is not so large. The variation in lime content is more complex in that whereas some lime was carried downwards by sinking of pyroxene, some lime was also carried upwards by the displacement upwards of the plagioclase in the residual magma. This movement of the plagioclase is brought out more clearly by the changes in the alumina and alkali content. These are more or less reciprocal to the changes in magnesia content.

The nearest approach to the original magma from which the Circular Head laccolith was derived, is provided by the little differentiated chilled base, and the chemical analysis of this phase (No. 1) indicates that it was a fairly typical undersaturated olivine-basalt magma (in the sense of Kennedy, 1933). The analyses closely resemble those of crinanites, except that they contain rather more potash (Walker, 1934). The potash content is not great enough, however, to enable the rock to be classified as teschenite, nor is the soda sufficiently high for this.

Petrography.

Chilled Base.

The chilled base at the contact with the underlying sediments is an almost cryptocrystalline rock, consisting of idiomorphic microphenocrysts of olivine, 0.1 to 0.2 mm. in diameter, set in a groundmass of minute grains of iron ore, olivine, prisms of pyroxene, microlites and minute twinned laths of plagioclase, needles of apatite, and abundant colourless glass. The olivine is partially altered to iddingsite, leaving a core of unaltered olivine, and a narrow rim of fresh olivine encloses the iddingsite. Where the olivine occurs as a groundmass constituent it generally encloses a minute core of iddingsite. Occasional microphenocrysts of moderately violet titanaugite occur, usually smaller than the olivine crystals. The bulk of the pyroxene, however, is present as minute violet prisms in the groundmass. These show extinction angles up to 45 degrees on the prism axis, and are presumably augite. The felspar microlites show practically straight extinction, while the laths with lamellar twinning extinguish at angles up to 15 degrees in the symmetrical zone. This indicates that the plagioclase is a basic oligoclase, of composition about Ab_{70}, which is borne out to some extent by the high soda content of the analysis of this rock (Table II., No. 1). Presumably the colourless glass also approaches this composition.

The most striking feature in the thin sections is the occurrence of numerous almost circular vesicles, 0.1 to 0.2 mm. in diameter, filled with acicular growths of what appears to be natrolite.

Twenty feet above the actual contact, the appearance of the rock has changed greatly. The olivine microphenocrysts average about 0.5 mm. in diameter, although some are as long as 1 mm. They have gathered into clots, and while they retain something of their original idiomorphic outline, they tend to be rounded and embayed. The iron ore grains are fewer, but coarser, and are associated with the clusters of olivine crystals. The interspaces between the clusters of olivine and iron-ore are divided up by long narrow plagioclase laths (averaging about 0.5 x 0.02 mm.), and sometimes larger (1.0 x 0.2 mm.), and the triangular interspaces between the laths are filled with prisms of violet-brown pyroxene, frequently gathered into rosettes or stellate groups. Patches of analcite, sometimes enclosing acicular natrolite, also occur in these interspaces. The plagioclase laths show extinction angles up to 30 degrees in the symmetrical zone, so that they consist of labradorite, of a composition about Ab_{45}. Even the apatite needles have partaken of the general increase in grain size.

THE OLIVINE-RICH LAYER.

The rock composing the layer of olivine accumulation, about 70 feet above the chilled base, shows a further change in texture. The titanaugite crystals have grown in size to prisms 0.5 x 0.2 mm. and have gathered into clusters, often preserving the stellate arrangement observed in the more crystalline part of the chilled base. In these clusters the titanaugite crystals are usually associated with the numerous coarser-grained, but rounded, crystals of olivine, and relatively coarse-grained crystals of iron-ore. Very little pyroxene remains in the groundmass, which consists essentially of plagioclase laths, crowded together, a little interstitial orthoclase, and analcite. The plagioclase is a basic labradorite (Ab_{35}), and has suffered partial analcitization. The individual laths are relatively small compared to the other minerals. The analcite in some of the interstices is intergrown with numerous more or less radially arranged inclusions of a purplish to brownish substance, which is generally opaque, and gives the impression of being extremely thin plates of titaniferous iron ore. Some of the brown inclusions, however, are very weakly birefringent, and show a minute cleavage pattern similar to that in the pyroxene, suggesting that it consists of thin plates of pyroxene. Some of the intergrowths are more or less granophyric in appearance.

At 100 feet above the chilled base the rock is essentially similar. The olivine, however, has undergone partial iddingsitization, and a wide rim of fresh olivine encloses the iddingsitized portion. The junction between the iddingsite and the outer olivine is sharply defined, but where cores of olivine are also present, the junction of the iddingsite with this inner olivine is fibrous and irregular. The felspar is still restricted to the groundmass, and is chiefly basic labradorite (Ab_{35}), but a small amount of interstitial orthoclase is also present. The apatite crystals have become noticeably coarse-grained, and appear as hexagonal cross sections and as large prisms.

ANALCITE-OLIVINE-TITANAUGITE-DOLERITE.

The bulk of the laccolith, the upper 320 feet, is composed of analcite-olivine-titanaugite-dolerite, in which the proportion of olivine decreases with elevation above the chilled base. In the uppermost 100 feet the olivine constitutes less than 10 per cent. of the rock, except in localized patches, and the titanaugite, which is the dominant ferro-magnesian, becomes increasingly ophitic towards the plagioclase, so that in the uppermost 50 feet of the laccolith the rock may be regarded as a true crinanite. Its richness in potash, however, reveals affinities with the teschenites.

The chief distinction between the dolerite and the olivine-rich layer is the increased coarseness of grain-size in the dolerite. Individual crystals of olivine and titanaugite frequently attain a diameter of 2 mm. or even larger, and the plagioclase laths show a comparable growth in size. The olivine has frequently undergone partial alteration to iddingsite, and consists of a core of olivine, mantled by a zone of iddingsite, which is enclosed in turn by a narrower rim of fresh olivine. The outer junction of iddingsite and olivine is sharply defined, but the inner one has a fibrous character, as in the upper part of the olivine layer. The titanaugite is distinctly pleochroic, with $X =$ yellow, $Y =$ deep violet, $Z =$ pale violet, and has a $(+)$ 2V about 60 degrees. The large crystals are frequently zoned, the marginal zones being a deeper violet than the inner ones. They sometimes show twinning and hour-glass structure. The titanaugite tends to enclose the smaller olivine crystals, and this habit becomes more marked with increasing height above the base. In some instance the olivine so enclosed has been completely altered to iddingsite, presumably prior to its enclosure by the titanaugite. The ferro-magnesian minerals and the iron ores have segregated into clusters, and the plagioclase laths form a triangular pattern in the interspaces. The plagioclase is basic labradorite (Ab_{35}). Patches of interstitial orthoclase are associated with it, and these appear to grow larger and more numerous near the top of the laccolith.

The proportion of analcite varies irregularly. It occurs in the interstices between the plagioclase laths, and frequently invades the plagioclase along cleavage planes and cracks. Where it makes contact with crystals of titanaugite there is a tendency for a narrow partial rim of aegirine-augite, or even aegirine to develop. Radial intergrowths of brown and purplish material such as were noted in the olivine-rich layer continue to be present in the analcite, and the coarse apatite prisms become a prominent feature in the sections. Sometimes, either owing to irregular crystallization or to partial resorbtion they form " atoll " growths.

Soda-rich Variations.

Although no variety more soda-rich than the crinanite of Analysis No. 4, Table II., was observed *in situ,* a number of lighter coloured boulders were observed in the screes and the beach deposits on either side of Circular Head. Specimens of these boulders proved to be much more sodic than the normal rock, and were found to contain notable amounts of analcite, and natrolite, and even a little nepheline.

The ferromagnesians form only a small part of these specimens. Olivine is subordinate to titanaugite, and both are present only as small crystals. The olivine is often enclosed in the pyroxene, and consists of a core of iddingsite enclosed by fresh olivine. The titanaugite has a (+) 2V about 60 degrees, and is invariably ophitic towards the plagioclase (Ab_{40}), which tends to occur in clusters of long narrow laths separating areas in which they are intergrown with the ferromagnesians. The titanaugite is commonly altered at the margin to a narrow rim of aegirine. Analcite is prominently developed, and has attacked the plagioclase to a considerable extent, but has not affected the orthoclase, which occurs relatively abundantly in the interstices of the plagioclase areas. Natrolite forms acicular growths in elongated and irregular-shaped areas of a vesicle-like character, and occasionally a corroded crystal of nepheline, preserving much of its idiomorphic outline, is present. Coarse prisms of apatite are numerous in association with the analcite and natrolite.

Nepheline-rich Phase.

A specimen still richer in soda occurs in the collection of the Geological Survey of Tasmania (No. 288). Chips of this specimen sufficient for analysis were placed at my disposal through the kindness of Mr. F. Blake, Acting Government Geologist of Tasmania, and the analysis is shown in Table II., No. 5, from which it will be seen that not only soda, but potash also, is concentrated in this specimen.

The rock has a greyish, weathered appearance in hand specimen, and is spotted with small irregular-shaped areas of zeolites, occasional porphyritic felspars 5 mm. long, and laths of pyroxene. On roughly polished surfaces it shows spherical intergrowths of radially arranged felspar and titanaugite. Thin sections reveal occasional small crystals of olivine, extensively altered to iddingsite and iron ore, but preserving their idiomorphic outline to some extent. The dominant ferromagnesian, however, is titanaugite, which occurs chiefly in relatively small crystals, and also forms graphic intergrowths with the analcitized plagioclase. It frequently shows a passage through aegirine-augite to aegirine at the margin. The aegirine rims are often as wide as the titanaugite core, and the transition zone is marked by precipitated iron ore. Individual crystals of aegirine also occur through the rock, though in much less abundance than the titanaugite. Plagioclase and orthoclase are present in more or less equal proportions. The plagioclase is labradorite (About Ab_{45}), and tends to occur as clusters of radially arranged laths. The orthoclase occurs as clear, broad areas filling the intersertal spaces and enclosing most of the other minerals. As shown in Table III. below, analcite and natrolite constitute about 16 per cent. of the rock, while nepheline forms about 8.5 per cent. of it. The nepheline occurs in numerous large rectangular and hexagonal crystals, which are somewhat corroded, and are veined by the analcite. It readily takes a stain with methylene-blue, using the method described by Shand (1939), but is not zoned. Coarse crystals of apatite, almost large enough to be classed as microphenocrysts, continue to be numerous, and the doubtfully identified brown to purplish material, found intergrown with the analcite throughout the laccolith, is also present. A little brown to emerald-green glass is also present, but iron ores are few, though coarse-grained. A micrometric analysis of several sections gave the following approximate composition:—

TABLE III.

Mineral.	Volume.
	%
Nepheline	8·6
Analcite, &c.	16·1
Plagioclase	34·8
Orthoclase	30·0
Titanaugite	4·6
Aegirine	2·8
Olivine	2·6
Iron ore	0·5
	100·0

Differentiation Processes.

The chief factor operating in the differentiation of the Circular Head laccolith appears to have been the differential sinking of the ferromagnesian minerals under the influence of gravity. The concentration of plagioclase in the upper levels was due to the reciprocal displacement upwards of the residual liquid by the sinking ferromagnesians.

The local concentrations of alkali-rich minerals call for a different explanation. The presence of corroded nepheline crystals, interstitial orthoclase, and titanaugite altered to aegirine proves that the concentrations of alkalis developed prior to complete solidification, though much of the analcite and natrolite may be of autopneumatolytic origin. Since the orthoclase occurs through the laccolith in minute interstitial patches, as one of the last minerals to crystallize, it is presumed that these local concentrations of alkaline minerals represent small pockets of the final residual liquid of the magma trapped in the otherwise more or less solidified mass. It may be noted in this respect that the plagioclase in the most rapidly chilled part of the laccolith base has the composition of oligoclase (Ab_{70}), while the plagioclase throughout the more slowly cooled part of the laccolith is labradorite (Ab_{35-45}). Hence, although sufficient soda (and potash) was present to convert the bulk of the labradorite to oligoclase, it failed to enter into the composition of the plagioclase. Instead it made its appearance as analcite, and so far as it was not all used up in this mineral, it must have entered into the final residuum of the magma.

The richness of the magma in mineralizers indicated by the abundance of analcite provides an explanation of the unusual occurrence of iddingsite. Previously iddingsite appears to have been recorded only from extrusive and hypabyssal rocks (Ross and Shannon, 1925). Its mode of occurrence is closely comparable with that of iddingsite formed during the actual process of extrusion in certain Victorian basalts, where a temporary concentration of mineralizers led to formation of iddingsite, with a subsequent reversal to olivine precipitation when the mineralizers were exhausted (Edwards, 1938). In both instances the iddingsite shows a fibrous reaction junction with the olivine which it replaces, but has a sharply defined junction with the rim of olivine that surrounds it, indicating a sudden cessation of reaction and return to the formation of olivine. Since the formation of iddingsite requires oxidizing conditions and the presence of abundant mineralizers, it must be assumed that such conditions were brought about in the laccolith by the relief of pressure that accompanied the doming up of the sedimentary roof.

Similar Occurrences in North-West Tasmania.

Two other laccoliths of analcite-olivine-dolerite occur along the coast of North-West Tasmania. One is the hill known as Mount Cameron West, which lies about 4 miles north of Marrawah, and rises to a height of about 200 feet. This striking hill is a "resumed island" (Edwards, 1941). It has suffered rather more irregular erosion than Circular Head, but in profile it preserves its dome-shape. Erosion at the seaward side has converted that part of the laccolith into a sharp crested ridge. At its eastern end, however, it retains its broad flattish top, which gives place to steep slopes on all sides. Close to sea-level, where it overlies flat-lying (?) Permo-Carboniferous sediments it has been chilled to a fine-grained olivine-basalt. Above this it becomes coarser-grained, but the thickness of the laccolith was not great enough to permit very much differentiation.

The other is the much larger laccolith of Table Cape near Wynyard, which is known to consist of rocks which are microscopically identical with those forming the Circular Head laccolith (Twelvetrees, 1902).

Age Relations.

The age of the Circular Head laccolith cannot be established with any certainty. It is older than the adjacent basalts of the Stanley Peninsula, because these were extruded in a valley that passes below sea-level, so that the valley bottom is at a lower elevation than the base of the laccolith. The laccolith was largely unexposed at the time of the basalt extrusion, because the Permo-Carboniferous beds enclosing it formed the east wall of the pre-basaltic valley. The top of the laccolith may have been uncovered, in view of the hanging valley situated there. The basalts of the Stanley Peninsula are regarded as being of Pliocene age (Nye and Blake, 1938).

At Mount Cameron West there is a similar lack of evidence. A Recent foraminiferal limestone abuts against the laccolith, and there are Miocene limestones in the vicinity, but the relation of the latter to the laccolith is not known. At Table Cape, basalt flows of Pliocene age abut against the laccolith, which had undergone extensive erosion prior to the extrusion of the basalts, and so is considerably older. Stephens (1908) reports that the Lower Miocene beds of Fossil Bluff also abut against the laccolith, but he was unable to say whether or not the contact was an intrusive one. Mr. F. A. Cudmore, however, informs me that this is not so, and that the Miocene beds pass below sea-level before reaching the laccolith. If the laccoliths are shown ultimately to be of pre-Lower Miocene age they may be linked with the pre-Miocene basalts of Marrawah (Nye and Blake, 1938); and it would be tempting to correlate them with the closely comparable crinanite and olivine-analcite-dolerite dykes of the Older Volcanic Series (Oligocene) in South Gippsland, Victoria (Edwards, 1934).

Acknowledgments.

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